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**COMPLEX ENVIRONMENTAL PATTERNS AND
HOLOCENE SEA-LEVEL CHANGES CONTROLLING REEF HISTORIES
ALONG NORTHEASTERN ST. CROIX, USVI**

BY

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AND JOYCE LUNDBERG**

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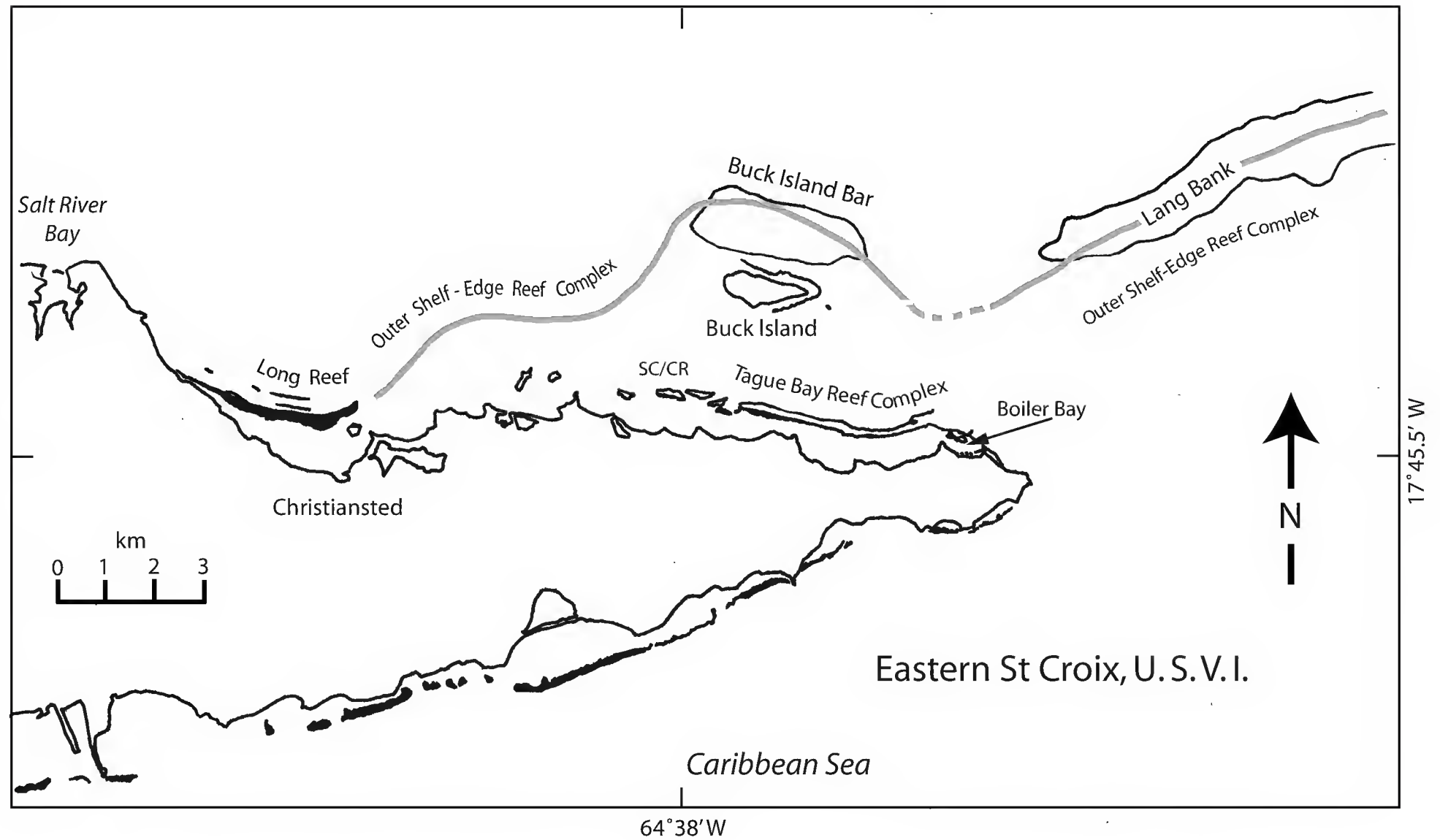


Figure 1. Index map of northeastern St. Croix showing Long Reef and the Outer Shelf-Edge Reef Complex (gray line), Buck Island, and the Inner Bank-Barrier Reef including Tague Reef, Sand Cay/Candlelight Reef (SC/CR), and Boiler Bay.

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ABSTRACT

The progressive timing of reef initiation along northeastern St Croix, and varying histories of reef growth, provide insights into the effects of Holocene paleoenvironmental and sea-level changes in the region, and into the importance of accurate and comprehensive sea-level reconstruction as context for understanding local variations in reef history. Two core transects provide new information on the Holocene history of related reef systems off the northeastern coast of St. Croix --- *the outer shelf-edge reef complex* ranging from northern Lang Bank through Buck Island Bar and ending at Long Reef, and *the inner bank-barrier reef* off Tague Bay. The outer shelf-edge reef system records progressively shallower and thinner marginal reef initiation and development above a westward-shallowing Pleistocene substrate; this surface rises from -15 m at Buck Island Bar to -6 m MSL at Long Reef. The core transect through the inner bank-barrier reef at Tague Bay reveals a 10-m thick accumulation of an *Acropora palmata*-dominated reef framework on a well developed 12-15 m deep erosional terrace.

A sea-level analysis for northeastern St. Croix indicates three periods in which different areas were the foci of reef initiation and development. The timing of initiation of reef systems along these reef trends as sea level rose during the Holocene follows the slope of the Pleistocene surface as it rises to the west, with the oldest (easternmost) reefs forming on the deepest areas of the antecedent topography. The westernmost reefs were initiated later as sea level reached the slightly higher elevations of the antecedent surfaces in these areas. The timing of Holocene reefs at these two sites is a direct result of the interaction of sea-level rise, antecedent topography, shelf erosion and evolving environmental conditions affecting coral health. The unique reef history at Buck Island Bar represents a particular case whose relationship to the Caribbean Holocene sea-level record supports paleoenvironmental interpretations potentially impacting all of Lang Bank to the east.

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INTRODUCTION

Reconstructing the history of reef growth is a multidisciplinary process requiring detailed understanding of local oceanographic and climatic conditions, and the relationship of regional sea-level history, local topography, erosion and other controls, to reef initiation and maintenance. Given this complexity, the geologic history of reef development may be temporally and spatially limited at any single reef site, and not always simply predictable from the regional sea-level curve. We report an interesting Caribbean case study from St. Croix, where the development of Holocene reefs in response to rising post-glacial sea level was dependent on variations in geologic and oceanographic factors along the northeastern coast. Reef structure and age were studied from the stratigraphy revealed by two core transects (14 cores in total, 5 not previously published), and from ^{14}C and U-Th dating of fossil coral samples (63 dates total, 10 of them new). With the availability of new core and age data and an additional reef transect site, a comprehensive regional synthesis of reef history, including multiple reef trends, is herein accomplished. The Holocene sea-level reconstruction for the Caribbean (Toscano and Macintyre, 2003) provides a well-constrained context for environmental changes and the relationship of sea level and antecedent topography to reef development over the Holocene in St. Croix. The results of the present study, which highlight significant local variation due to sea-level change, antecedent topography and the response of individual species to evolving local conditions, have general implications for the reconstruction of reef history and sea level using core data.

The insular shelf off the northeast coast of St. Croix exhibits a variety of Holocene sediment and reef accumulation patterns. Two separate linear reef trends have been previously mapped and cored (Adey et al., 1977; Burke et al., 1989; Macintyre and Adey, 1990; Hubbard, 1991; Hubbard et al., 2005), describing reef development around the eastern end of St Croix. The *outer shelf-edge reef complex* trends westward from northeastern Lang Bank on its eastern end, through Buck Island Bar, and ending at Long Reef (offshore of Christiansted). Lang Bank, a major feature of the shelf edge all around eastern St Croix (Adey et al., 1977) forms the northeastern end of the outer shelf-edge reef system (Fig. 1). Lang Bank started reef building along its southwestern arm during the early Holocene (~10,000 yrs BP; Adey et al., 1977), and began building a thick accumulation of *Acropora palmata* framework on its northeastern end at approximately 7,700 cal BP (Hubbard et al., 2005). The depth to the Pleistocene surface is not known but is estimated to be below -15 m mean sea level (MSL). To the west, Buck Island Bar (Fig. 1) has >10 m of accumulation of mainly *A. palmata* and sand from one core along the shelf edge (Hubbard, 1991; Hubbard et al., 2005). The reef forming Buck Island Bar was established on an elevated Pleistocene ridge at ~-15 m MSL prior to 7,700 years ago, but ceased active framework construction approximately at ~1,200 cal BP, as indicated by a near-surface dated *A. palmata* of 1,180 cal BP at a depth of about 5 m below present sea level (Hubbard et al., 2005).

Macintyre and Adey (1990) drilled a core on Buck Island Bar just shoreward of the core of Hubbard et al. (2005) and recovered mostly massive corals and well-lithified pavement limestone, a facies pattern signifying slow accumulation under exposed,

high-energy conditions. In addition, the surface of this reef has remained below -4.5 m, never reaching sea level in elevation, during the last 4000 years. Adey and Macintyre (1990) concluded that any *A. palmata* accumulations at this site were likely to have been frequently damaged and transported shoreward by heavy seas or severe storms, thus not allowing this reef to keep up with sea level.

Hubbard et al. (2005) also indicated that while *A. palmata* was becoming well established as the primary reef framework builder on the outer shelf edge (Buck Island Bar and Lang Bank), by 7,500 cal BP a predominance of massive head corals was just becoming established across inner shelf areas. They also reported reductions in *A. palmata* on the outer shelf edge by 7000 cal BP, which became absent from Buck Island as well as possibly less plentiful throughout the Caribbean by 6000 cal BP. By 5,000 cal BP *A. palmata* was again making a major contribution to the framework of outer shelf-edge reefs as well as the bank-barrier reefs of Buck Island, which eventually caught up with sea level. Tague Reef on the inner shelf was still head-coral dominated (Hubbard et al., 2005).

The up to 10-m thick sections of the inner-shelf Tague Bay reef system are related to the elevation of the Pleistocene substrate in the area. This antecedent surface dips to the east, allowing early initiation of reef framework construction at Tague Bay by 7030 cal BP, following the reefs at Buck Island Bar (7700 cal BP; Hubbard et al., 2005). Candlelight Reef, an isolated westward extension of the Tague Bay inner reef system, was established as a fringing reef on the Pleistocene terrace underlying Sand Cay, a shore-parallel clastic bar. Burke et al. (1989) show a shore-parallel cross section of Tague Reef, along which several cores intersect the Pleistocene surface at depths of ~-9 m (Sand Cay/Candlelight Reef – SC/CR; Fig. 1), ~-11 to -13 m (Tague Reef; Fig. 1) and -14 m (Romney Point - RP; Fig. 3). At the eastern end of Tague Bay, Adey (1975) cored the algal ridges in Boiler Bay (Fig. 1) to determine timing of initiation on top of ridges of the Caledonia Formation as well as on a “bench of Caledonia boulders” (page 7) i.e., colluvium from the Caledonia Formation. This surface occurred along the W-E sloping trend from -21 m, rising to benches at -5 m MSL (Adey 1975, Fig. 7). Algal ridges formed after sea-level rise eroded the colluvium, allowing establishment of *A. palmata* colonies on the lobes and benches of lag conglomerate, followed by algal ridges and boilers.

Long Reef, the westernmost extension of the outer shelf-edge reef complex, resting on the landward edge of the pre-Holocene surface, is the essential (and previously missing) end-member of the geologic history of this reef system. We present for the first time a 5-core transect drilled across Long Reef. We compare this northwestern limit of the shelf-edge reef system with its eastern extension as far as Buck Island Bar. We also provide new stratigraphic and age data from a core transect across the Tague Bay reef complex to better document its Holocene history and response to local conditions and regional sea-level rise (SLR) over the past 11,000 yrs. Eight of these cores across the reef complex are presented in this study, with an earlier core (16) from Burke et al. (1989). A diagrammatic sketch of this transect was included in Burke et al. (1989).

METHODS

A diver-operated hydraulic drill (Macintyre, 1975) was used to collect 54 mm diameter cores along a transect across the Tague Bay reef system (Fig. 2) during two field trips in May and July/August 1976. Ten cores (eight used in this study, Fig. 3) were collected along a transect extending from the West Indies Laboratory pier, across the back-reef lagoon, and the Tague Bay bank-barrier reef to the bottom of the outer slope at a depth of 14.9 m (Burke et al., 1989). Core 16 (Burke et al., 1989) is added to this cross section.

In November 1978, five cores were drilled across the northwestern limit of the shelf-edge reef system at Long Reef (Fig. 4; 5). These cores extended from the back-reef lagoon (Core 5, Fig. 5) across the reef crest (Cores 1 and 2, Fig. 5), to two cores drilled adjacent to each other on a slight spur (Core 4, Fig. 5) and groove (Core 3, Fig. 5).

We herein document all previously published radiocarbon dates (Burke et al., 1989; Macintyre and Adey, 1990; Hubbard, 1991; Hubbard et al., 2005), and add ten new dates, including four Thermal Ionization Mass Spectrometric U-Th dated samples, to the St. Croix database (Table 1). Radiocarbon dates from the Tague Bay transect were analyzed in the mid-late 1970s by Robert Stuckenrath of the Smithsonian Radiocarbon Dating Laboratory. The dates for the Long Reef transect were analyzed in the 1970s by Beta Analytic Inc., Coral Gables, Florida. These original radiocarbon dates were not corrected for $\delta^{13}\text{C}_{\text{PDB}}$ and did not incorporate an oceanic reservoir correction, hence some were published as basic ^{14}C dates based on the Libby half life (5568 years). Conventional radiocarbon ages, which are now routinely reported, have been corrected for isotope fractionation by normalizing $\delta^{13}\text{C}$ to 0‰_{PDB} for corals. For these samples we have calculated $\delta^{13}\text{C}_{\text{PDB}}$ values using the Calib spreadsheet d13ccorr.xls (linked from the online Calib manual; <http://calib.qub.ac.uk/calib>), assuming the original measurement was a $^{14}\text{C}/^{12}\text{C}$ ratio. The $\delta^{13}\text{C}$ correction spreadsheet also calculates the corresponding conventional radiocarbon date for each sample. Next, all coral radiocarbon dates were calibrated using the Calib 5.1.0 Beta program (Stuiver and Reimer, 1993; <http://calib.qub.ac.uk/calib>; on-line version Stuiver et al., 2005), the marine calibration dataset (marine 04) and a time-dependent global ocean reservoir correction (~400 years; CALIB Manual version 4.1, Stuiver and Reimer, 1993). The difference in age between the local ocean reservoir and modeled values (ΔR) was set at -5 ± 20 (Darden Hood, Beta Analytic, pers. comm.; Stuiver and Braziunas, 1993).

Thermal Ionization Mass Spectrometric (TIMS) U-Th dating was done in the Isotope Geochemistry and Geochronology Research Facility, Carleton University, Ottawa, Ontario, following standard techniques (e.g., Ivanovich et al., 1992). Samples were ultrasonically cleaned, ignited for 5 hours at 875° C to remove organics, dissolved in HNO_3 and spiked with ^{233}U - ^{236}U - ^{229}Th tracer. U and Th were co-precipitated with iron hydroxide, and purified twice on anion exchange columns (Dowex AG1-X 200-400 mesh). Measurement of U and Th isotopic ratios was done on the Triton TIMS, in peak jumping mode using secondary electron multiplier with retarding quadrupole filter. Ages were calculated using half lives from Cheng et al. (2000).



Figure 2. Aerial photograph looking east along Tague Bay bank-barrier reef. Arrow indicates drill site.

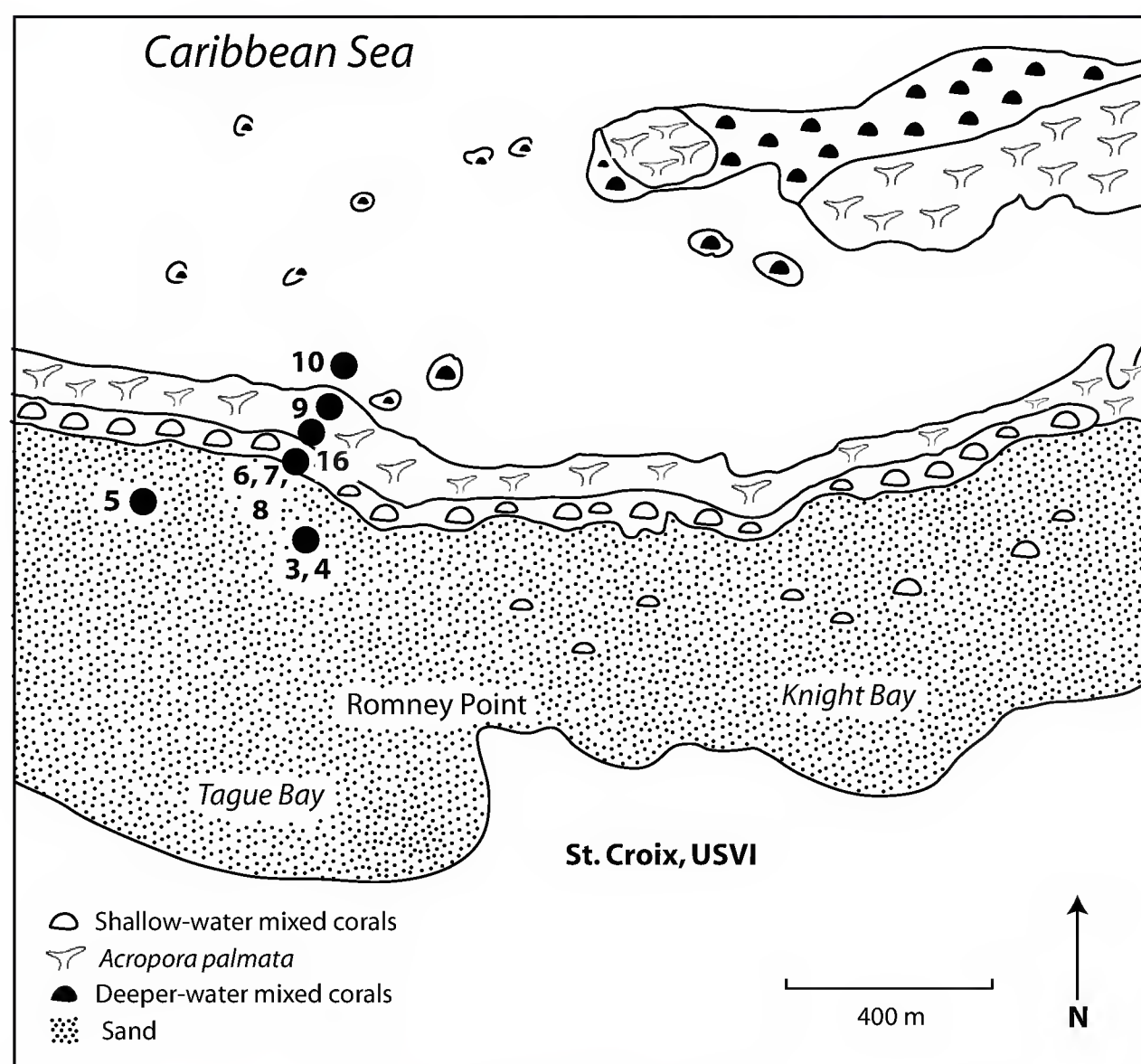


Figure 3. Index map showing the general distribution of the bottom communities and the location of the nine core sites (the numbered solid circles) across Tague Bay bank-barrier reef.

Table 1. Compilation of all radiocarbon (59 samples) and TIMS (4 samples) age data for Buck Island Bar (BB or BIB, HSX = haystacks), Long Reef (LR), Buck Island (BI), Tague Bay, Tague Reef, Sand Cay Reef, and Sand Cay/Candlelight Reef (TB, TR, SCR, SCC), northeastern St. Croix. The 14C data are from: 1- this study; 2 - Burke et al. (1985); 3 –Macintyre and Adey (1990); 4 – Hubbard et al. (2005).

Sample ID	Site Name (reference)	Coral Species	Depth (m MSL)	¹⁴ C date	Error	Conventional Age (yrs BP)	Age Error	cal BP or TIMS U-Th δ
BB1-23	Buck Island Bar ⁴	<i>A. palmata</i>	-12.75	6950	80	7360	80	7770
BB1-26	Buck Island Bar ⁴	<i>A. palmata</i>	-13.7	6860	90	7270	90	7670
BIB4 H1C5_1978	Buck Island Bar ³	<i>A. palmata</i>	-12.39	4145	50	4552	50	4763
BIB3 H1C3_1978	Buck Island Bar ³	<i>P. astreoides</i>	-9.32	3555	50	3962	50	3970
BIB2 H1C2_1978	Buck Island Bar ³	<i>M. annularis</i>	-8.0	2745	50	3152	50	2943
BB1-11	Buck Island Bar ⁴	<i>A. palmata</i>	-8.15	1990	70	2400	70	2005
BIB2 H1C1_1978	Buck Island Bar ³	<i>Diploria</i> sp.	-6.02	1785	45	2192	45	1792
BB1-2	Buck Island Bar ⁴	<i>A. palmata</i>	-5.05	1220	70	1630	70	1180
LR H4 C2	Long Reef ²	<i>A. palmata</i>	-6.08	3890	70	4297	70	4427
LR H2 C3	Long Reef ²	<i>D. clivosa</i>	-4.17	3620	60	4027	60	4052
LR H2 C2	Long Reef ²	<i>A. palmata</i>	-3.08	3250	120	3657	120	3596
LR H1 C2	Long Reef ²	<i>M. annularis</i>	-4.43	1970	50	2377	50	2007
LR H2 C1	Long Reef ²	<i>D. strigosa</i>	-2.02	700	50	1107	50	663
LR H4 C1	Long Reef ²	<i>A. palmata</i>	-5.52	270	50	677	50	349
BI1-52	Buck Island ⁴	<i>M. faveolata</i>	-12.5	----	----	7070	120	7510
BI4-39	Buck Island ⁴	<i>M. faveolata</i>	-8.2	----	----	6680	90	7175
BI1-40	Buck Island ⁴	<i>M. faveolata</i>	-11	----	----	6330	80	6775
BI4-21	Buck Island ⁴	<i>M. faveolata</i>	-5.9	----	----	5760	80	6180
BI3-49	Buck Island ⁴	<i>M. faveolata</i>	-10.5	----	----	5320	70	5665
BI2-50	Buck Island ⁴	<i>A. palmata</i>	-14.25	----	----	4930	80	5270
BI4-14	Buck Island ⁴	<i>A. palmata</i>	-4.9	----	----	4860	70	5190
BI1-24	Buck Island ⁴	<i>A. palmata</i>	-7.15	----	----	4440	100	4570
BI3-37	Buck Island ⁴	<i>M. annularis</i>	-8.5	----	----	4370	90	4495
BI2-43	Buck Island ⁴	<i>M. faveolata</i>	-11.8	----	----	4220	120	4305
BI5-62	Buck Island ⁴	<i>S. sidera</i>	-14.25	----	----	4150	80	4210
BI1-13	Buck Island ⁴	<i>A. palmata</i>	-5.45	----	----	4010	80	3990
BI4-02	Buck Island ⁴	<i>D. labyrinthiformis</i>	-2.35	----	----	3500	60	3365
BI1-02	Buck Island ⁴	<i>A. palmata</i>	-3.90	----	----	3440	70	3320
BI7-29	Buck Island ⁴	<i>M. faveolata</i>	-16.05	----	----	3090	70	2840
BI2-27	Buck Island ⁴	<i>M. faveolata</i>	-7.85	----	----	2950	70	2725

Table 1, Con'td. ¹⁴C **Date** represents the original, uncorrected basic radiocarbon date. **Conventional Age** is corrected for $\delta^{13}\text{C}$. **Cal BP** is the calendar age calibrated from marine calibration data and corrected for the oceanic reservoir effect. Cal BP ages are curve intercepts with probability ranges. Here we provide the curve intercept dates. Under Sample ID * denotes a replicate date. **U-Th dates** are denoted by \diamond and error range.

BI7-20	Buck Island ⁴	<i>M. faveolata</i>	-12.25	----	----	2620	80	2305
BI2-27*	Buck Island ⁴	<i>M. faveolata</i>	-7.85	----	----	2755	65	2225
BI2-05	Buck Island ⁴	<i>A. palmata</i>	-4.6	----	----	2250	80	1840
BI2-05*	Buck Island ⁴	<i>A. palmata</i>	-4.6	----	----	2310	70	1780
BI2-01	Buck Island ⁴	<i>A. palmata</i>	-3.35	----	----	2175	70	1740
BI5-40	Buck Island ⁴	<i>M. faveolata</i>	-8.35	----	----	2020	70	1555
BI2-16	Buck Island ⁴	<i>A. palmata</i>	-2.05	----	----	1830	60	1345
BI5-22	Buck Island ⁴	<i>A. palmata</i>	-4.65	----	----	1540	60	1075
BI5-24	Buck Island ⁴	<i>A. palmata</i>	-6.2	----	----	1510	70	1045
BI5-12	Buck Island ⁴	<i>A. palmata</i>	-2.9	----	----	1450	70	970
HSX-1	Buck Island ⁴	<i>A. palmata</i>	-7.9	----	----	1310	60	865
BI7-7	Buck Island ⁴	<i>M. faveolata</i>	-7.9	----	----	750	60	400
HSX-2	Buck Island ⁴	<i>A. palmata</i>	-7.9	----	----	660	60	285
BI7-2	Buck Island ⁴	<i>A. palmata</i>	-5.75	----	----	620	60	265
BI6-6	Buck Island ⁴	<i>M. faveolata</i>	-13.1	----	----	590	50	250
BI3-05	Buck Island ⁴	<i>D. clivosa</i>	-0.5	----	----	540	60	150
SCR-3D C17	Tague Bay Romney Pt ¹	<i>A. palmata</i>	-10.4	6135	80	6542	80	7052
SCR-2 C17	Tague Bay Romney Pt ¹	<i>A. palmata</i>	-7.2	5490	85	5897	94	6329
TB H8 C2b	Tague Bay ¹	<i>A. palmata</i>	-8.62	4525	80	4932	80	5235
H7 C2-4	Tague Reef ²	<i>M. annularis</i>	-12.3	----	----	----	----	\diamond 3889 \pm 8
TB Core 15	Tague Bay ²	<i>Diploria</i> sp.	-8.0	3415	80	3822	80	3779
TB H8 C2	Tague Bay ¹	<i>A. palmata</i>	-7.98	3220	75	3627	75	3541
TR H7 C2-1	Tague Reef ²	<i>Diploria</i> sp.	-7.75	----	----	----	----	\diamond 2295 \pm 4
TB Core 15	Tague Bay ²	<i>M. annularis</i>	-3.0	2035	80	2442	80	2090
TB Core 13	North Shore Reef ¹	<i>A. palmata</i>	-2.7	1850	65	2257	65	1870
TR H8 C1-5	Tague Reef ²	<i>A. palmata</i>	-4.8	----	----	----	----	\diamond 1873 \pm 5
TR H6 C1-6	Tague Reef ²	<i>M. annularis</i>	-5.5	----	----	----	----	\diamond 1661 \pm 3
TB Core 11	Sand Cay/Candlelight Reef ²	<i>A. palmata</i>	-3.0	1495	60	1902	60	1449
TB Core 13	North Shore Reef ²	<i>M. annularis</i>	-2.0	1455	80	1862	80	1432
TB H9 C2	Tague Bay ¹	<i>A. palmata</i>	-7.9	1115	65	1522	65	1082
TB Core 17	Tague Bay Romney Pt ²	<i>A. palmata</i>	-1.0	803	50	1210	50	774
SCC-3 C19	Tague Bay Romney Pt ²	<i>A. palmata</i>	-1.2	720	80	1127	90	708
TB Core 16	Tague Bay ²	<i>A. palmata</i>	-1.5	120	80	527	80	152



Figure 4. Aerial photograph looking east across Long Reef (shelf-edge reef).

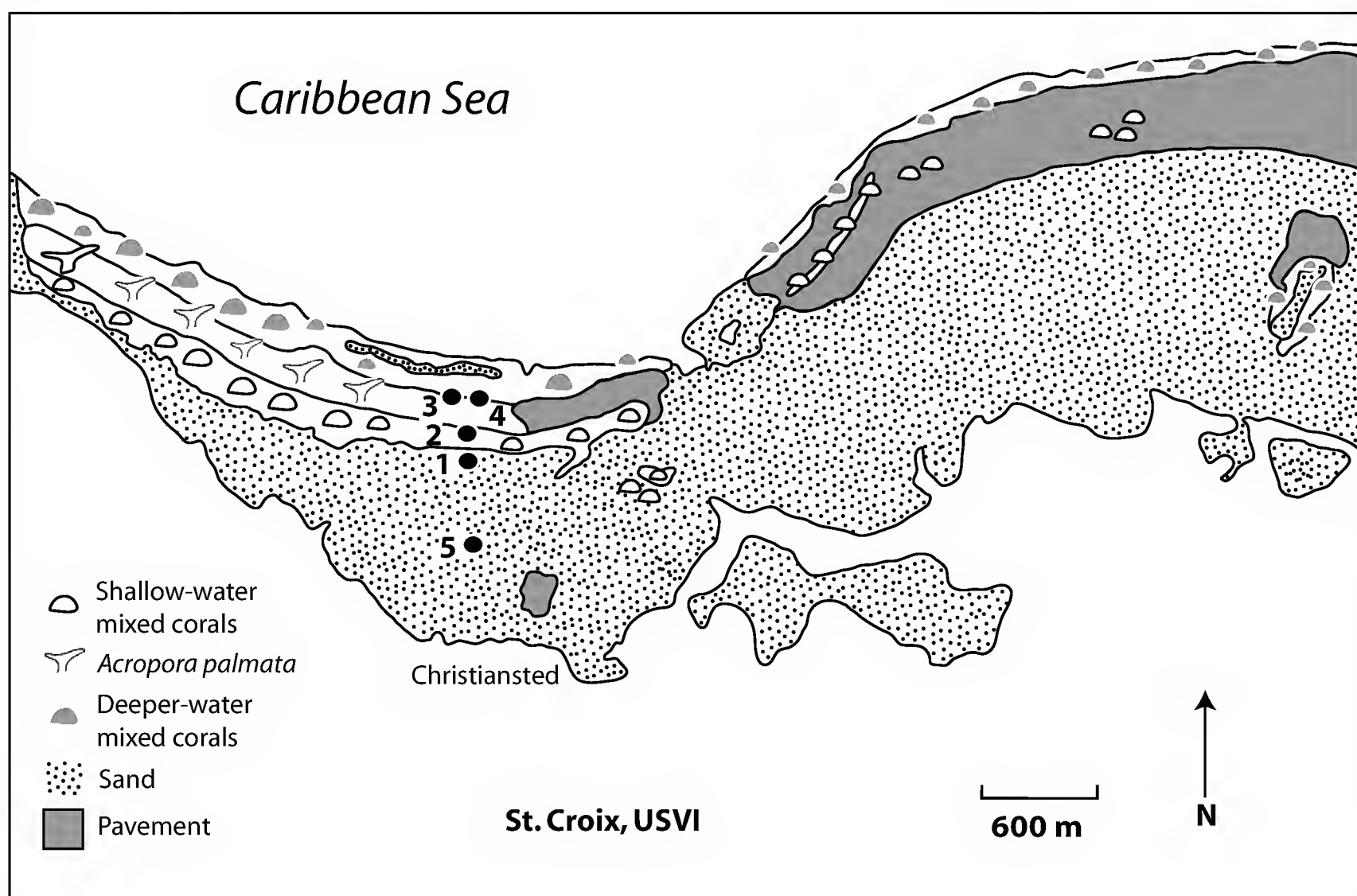


Figure 5. Index map showing the general distribution of the bottom communities and the location of the core sites (the numbered solid circles) across Long Reef.

RESULTS

Drill Site Descriptions

Descriptions of the two drill site settings were made in the mid 1970s. Drilling was completed prior to the major loss of *Acropora palmata* and *Acropora cervicornis* to White Band Disease in this area in the late 1970s and early 1980s (Gladfelter, 1982) and the regional mass mortality of *Diadema antillarum* in the early 1980s (Lessios et al., 1984). Site descriptions start at the western end of the older outer shelf-edge reef complex (Long Reef), then the inner bank-barrier reef (Tague Reef).

Long Reef - Outer Shelf-Edge Reef. The shallow back-reef zone (~1 m) consists of a crustose coralline algal encrusted coral-rubble flat with patches of *Thalassia*-covered sand and mounds of *Porites porites*. Other scattered corals on this rubble included *A. palmata*, *Diploria clivosa*, *Diploria strigosa*, and *Montastraea annularis*. This coral-rubble bottom became more lithified (Fig. 6) on approaching the reef crest, with both *A. palmata* and *Porites astreoides* becoming more dominant and with the addition of *Millepora complanata*. At the time of our field work *D. antillarum* were very abundant and coral colonies and fragments of Caledonia Formation stood out in relief from the surrounding urchin-eroded substrate (Fig. 7).

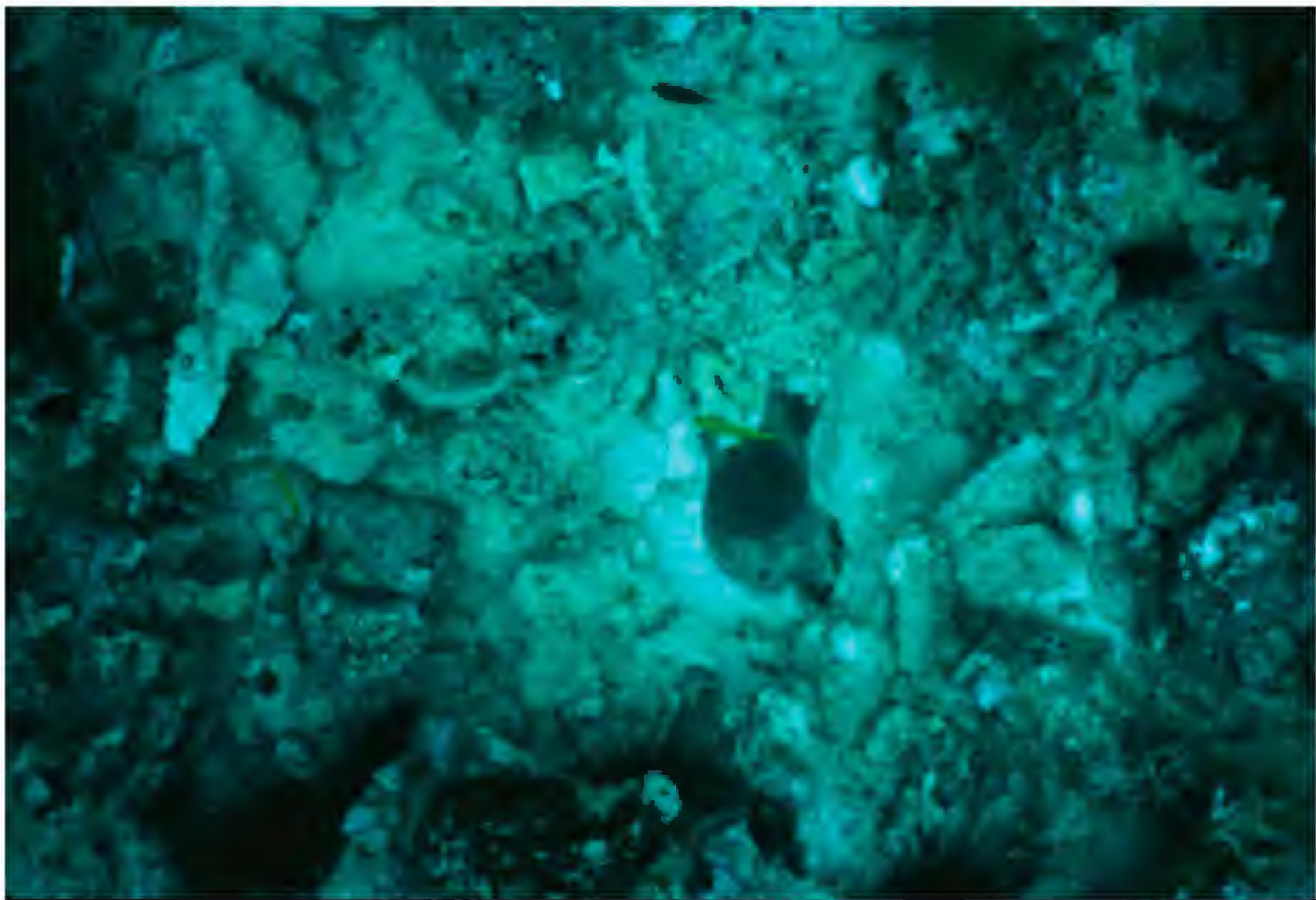


Figure 6. Dense interlocking and lithified coral rubble reef flat close to reef crest at Core 2 site, Long Reef.



Figure 7. Bioerosion of reef-flat pavement by *Diadema antillarum* has left Caledonia Formation rubble standing out in relief, Long Reef.

The *A. palmata*-dominated reef crest sloped gently seaward to form a low-relief (~1 m) spur and groove pattern (Fig. 8). The spurs had coral cover consisting of *A. palmata*, *M. annularis*, *D. strigosa*, *D. clivosa*, *Millepora* spp., *M. cavernosa*, *Siderastrea siderea*, *Siderastrea radians*, with some *Agaricia agaricites*, *P. porites*, *Dichocoenia stokesi*, *Mussa angulosa*, *Meandrina meandrites*, and *D. labyrinthiformis*. The zoanthid *Palythoa caribaeorum* was also very abundant. The adjacent grooves had a much denser and smooth substrate (Fig. 9) with scattered *A. palmata* and small colonies of *D. strigosa*, *Dichocoenia stokesi*, *M. cavernosa*, and *Stephanocoenia michelinii*.

This spur and groove gave way seaward to a smooth pavement with increasing coverage of octocorals at about 8 m (Fig. 10). This community changed to thickets of *A. cervicornis* at 12 to 14 m. The slope then became covered with a few large colonies of *M. annularis* and scattered colonies of *S. siderea*, *M. cavernosa*, *A. agaricites*, *P. porites*, *D. strigosa*, *D. clivosa*, *D. labyrinthiformis*, *D. stokesi*, *Colpophyllia natans*, and *Dendrogyra cylindrus*. The overall impression of the bottom community in this area was that there was very little Holocene framework accumulating. There was extensive bioerosion, with coral colonies mostly small and scattered over a hardground (Fig. 10). There was no indication of the buttresses and pinnacles with downward slumping massive coral blocks that had been reported on the outer reef slopes west of our site at Salt River (Hubbard et al., 1986) and Cane Bay (Hubbard et al., 1990).



Figure 8. Shallow fore-reef spur and groove zone, Long Reef. Spur covered dominantly by *Montastraea annularis* and *Millepora complanata* in contrast to the almost bare groove. Depth 5 m.



Figure 9. Close-up photo of Core 3 in a groove along the shallow fore reef of Long Reef. Note the smooth surface with no significant encrusting organisms. Coring revealed that this is a Pleistocene limestone surface. Depth 6 m.



Figure 10. Octocorals and scattered coral heads on a hardground with very little sediment cover on the fore-reef slope of Long Reef. Depth 8 m.

Tague Bay - Inner Bank-Barrier Reef. Starting at a lagoon depth of about 6 m, the bottom was dominated by the seagrass *Thalassia testudinum* along with the calcareous green algae *Halimeda* spp. and *Penicillus* sp. (Burke et al., 1989). The back-reef area consisted of coral patches, including *P. porites*, *M. annularis*, *D. strigosa*, and *C. natans* with scattered octocorals, and surrounded by sand (Fig. 11). This graded upward to a dense *A. palmata* community at the reef crest (Fig. 12), which also included *D. strigosa*, *M. complanata* and *P. astreoides* (Dahl et al., 1974). This reef crest is about 50 m wide and falls off to a seaward slope covered with a variety of corals including *D. strigosa*, *M. annularis*, *S. siderea*, *Agaricia* sp., *A. cervicornis*, *M. cavernosa*, *D. labyrinthiformis*, *C. natans*, *Meandrina* sp., *Mycetophyllia* sp., *P. furcata*, and *M. angulosa* (Dahl et al., 1974). This slope leveled off to a sandy bottom at a depth of 15 m.

Core Transects

Long Reef Transect (westward end of outer shelf-edge reef trend). Four cores from this shelf-edge reef contain no more than approximately 4.5 meters of reef accumulation above the Pleistocene erosional surface at ~-6 to -7 m MSL (Fig. 13). The oldest radiocarbon date of 4427 cal BP (at -6 m MSL) on *A. palmata* in the outer spur indicates that reef initiation in this area probably occurred less than 5,000 years ago. Core 2, drilled immediately leeward of the reef crest, yielded a head coral date of 4052 cal BP at -4 m MSL, and a date of 3,596 cal BP on *A. palmata* at -3 m MSL. Much of the material from the two reef-flat cores (Cores 1 and 5, Fig. 13) consisted of leeward-transported coral/



Figure 11. Drilling Core 7 in the shallow back reef of Tague Bay reef. Note the coral patches with surrounding sand.



Figure 12. The reef crest of Tague Bay reef showing the dense coral framework that includes *Acropora palmata*, *Diploria strigosa*, and *Millepora complanata*.

reef debris. The most striking feature of this cross section is the exposure of Pleistocene substrate at -6 m MSL in the low-relief fore-reef grooves (Core 3, Fig. 13). The pavement areas seaward of the spur and groove (Fig. 12) are probably exposed Pleistocene limestone.

Tague Bay Reef Transect (inner-shelf reef). The bank-barrier reef at Tague Bay was established on a 100 m-wide terrace at a depth of about -12 m (Fig. 14). Tague reef has many of the internal facies characteristics of a typical Caribbean *A. palmata* coral reef (Macintyre and Glynn, 1976). Its central section is dominated by *A. palmata* framework, while the shallow wave-washed section is more lithified by submarine cement (Macintyre, 1977). Massive coral colonies, particularly *M. annularis* and *D. strigosa*, are concentrated at the base and back-reef zone, while lagoonal sediments limit reef framework construction to the leeward. Burke et al. (1989) obtained only one radiocarbon date at the reef crest (152 cal BP, Core 16); additional dates were reported leeward (Core 8) and seaward (Core 9) of the crest. We report four new high-precision Thermal Ionization Mass-Spectrometric (TIMS) U-Th dates in back-reef Cores 6 (1661 ± 3 yrs at -5.5 m MSL, *M. annularis*), 7 (3889 ± 8 yrs at -12.3 m MSL, *M. annularis*; 2295 ± 4 yrs at -7.75 m MSL, *Diploria* sp.), and 8 (1873 ± 5 yrs at -4.8 m MSL, *A. palmata*). We have no radiocarbon dates at the base of this reef (\sim -12 m under the reef crest; -15 m under the fore-reef); the oldest available date on *A. palmata* is 5235 cal BP at a depth of -8.62 m MSL. This date/depth is stratigraphically consistent with a date of 7060 cal BP on *A. palmata* at -10.4 m MSL in a core 40 meters to the east (Core 17 at Sand Cay Reef; Burke et al., 1989). We therefore conclude that Tague Reef framework was established at approximately 7,000 years ago (when sea level was \sim -7.5 m MSL), building upward and expanding seaward, with the leeward Cores 7 and 6 documenting the back-reef facies. The youngest dates in these back-reef cores indicate the rapid accumulation of back-reef talus after the reef crest approached sea level \sim 2000 yrs ago.

DISCUSSION

The outer shelf-edge and inner shelf-core transects document two separate but roughly coeval coral reef systems whose histories were controlled by antecedent topography and SLR along the northeastern coast of St. Croix. The Long Reef transect represents the western end of the outer shelf-edge reef complex which formed progressively from east to west on a westward-shallowing pre-Holocene surface (Hubbard et al., 2005). The Tague Bay transect of the inner shelf reef complex occurs inside the outer shelf-edge reef trend but is correlative with the portion of the outer reef trend that lies directly to the north (Buck Island Bar), both temporally and in elevation range. Buck Island Reef initiated in between these two trends on a “broad antecedent bench” from -13 to -16 m MSL around Buck Island (Hubbard et al., 2005), but dated *A. palmata* from the upper sections indicate the reef framework is generally contemporaneous with that of Long Reef.

In his study of the algal ridges near Tague Reef at Boiler Bay (Fig. 1), Adey (1975) emphasized the “importance of pre-existing shelf level in determining the form and developmental stage of ridge-reef systems.” Along each reef trend, the timing of reef

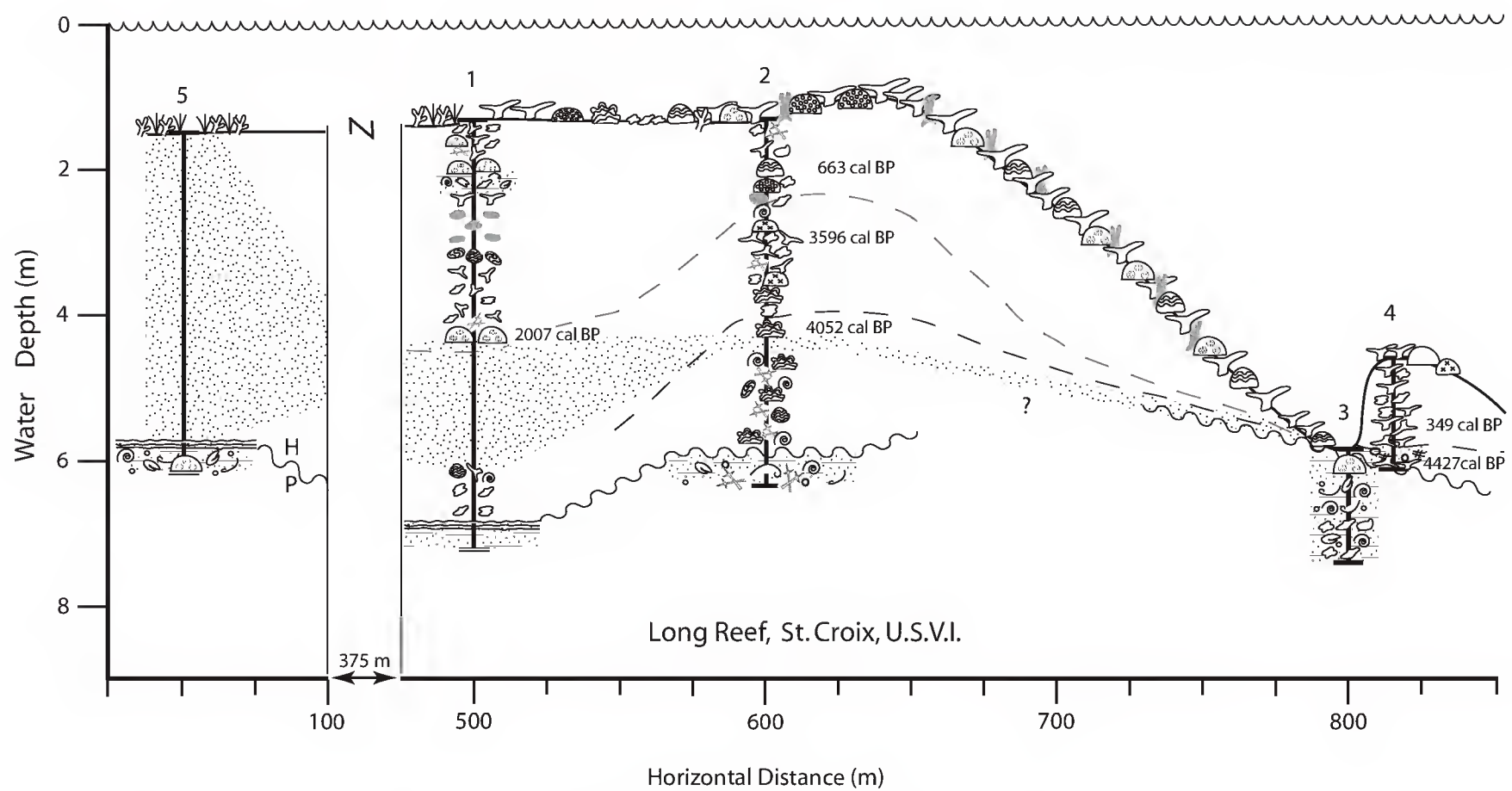


Figure 13. Cross section of Long Reef along the core transect showing the core data and location of radiocarbon dates.

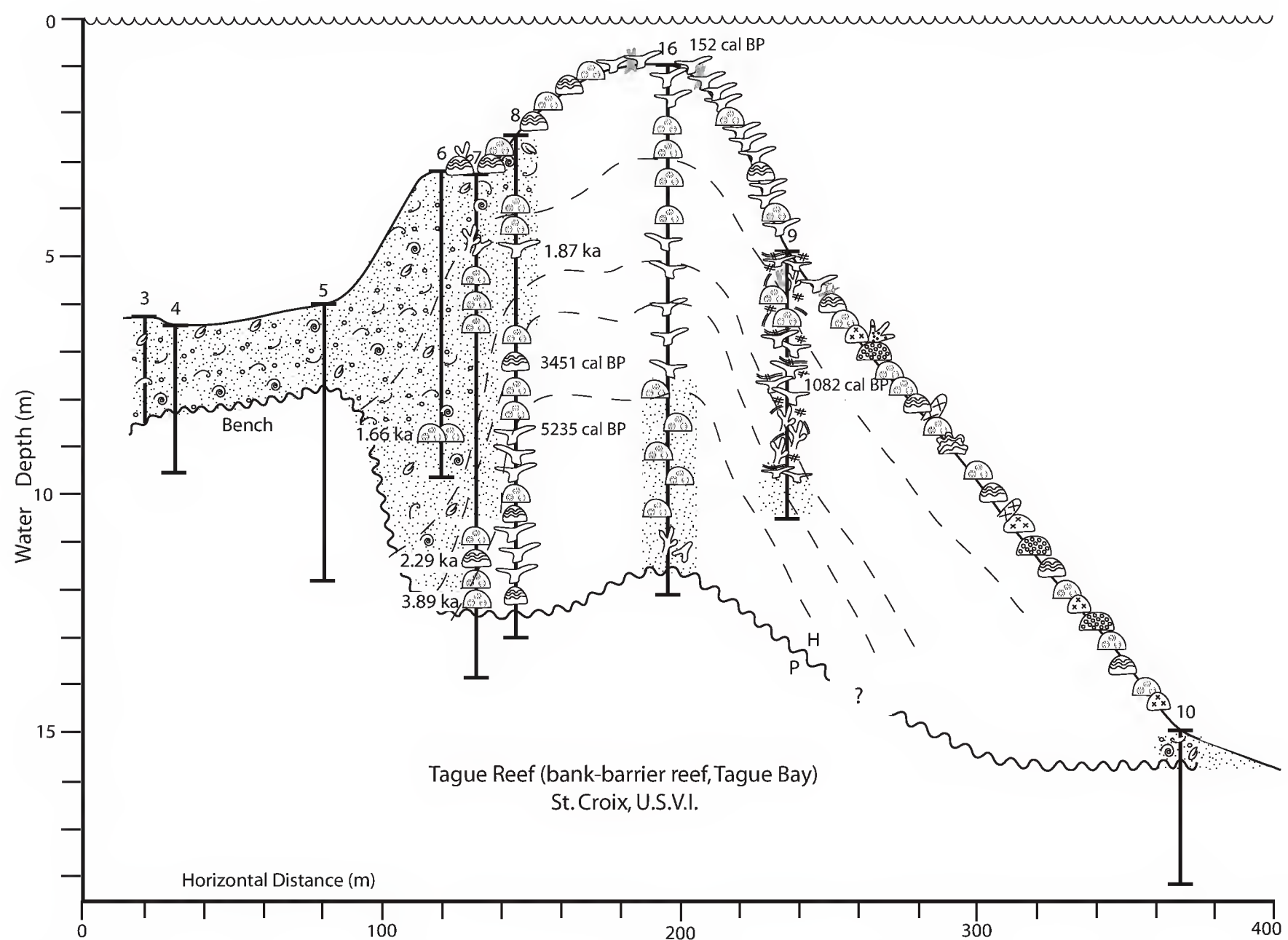


Figure 14. Cross section of Tague Bay reef along the core transect, showing the core data and the location of radiocarbon dates.

initiation, thickness of accretion and duration of accumulation were directly related to the elevation of the antecedent topography, local substrate character, rate of SLR and marine environmental factors affecting coral growth (e.g. initial turbidity followed by improving water quality over time vs. deepening water and decreasing light levels) at each site as sea level rose over the shelf. Macintyre (1988) introduced the concept of Holocene coral reefs keeping pace with SLR, indicating that the thickness of accumulation in any area is controlled by variations in the pre-existing shelf topography, but is initially inhibited by shelf flooding, soil erosion and subsequent turbidity. Mineralogic evidence in support of the shelf soil erosion hypothesis has been presented by Adey et al. (1977) along the southern extension of the shelf-edge reef system. As the Holocene transgression proceeded, turbidity would have eventually subsided and reefs formed shoreward in areas shallow enough to support *A. palmata* reef crest framework close to sea level. A sea-level based general history of northeastern St Croix reefs can be constructed from these data. The western Atlantic sea-level (WASL) curve of Toscano and Macintyre (2003) is used as a reference standard in this area (see also Hubbard et al., 2005).

Time-depth plots of all calibrated radiocarbon dates from northeastern St Croix reefs against the western Atlantic sea-level (WASL) curve (Toscano and Macintyre, 2003; Fig. 15A-D) give the overall history of the progressive east to west flooding of the westward-shallowing pre-Holocene erosional surfaces, followed by reef accumulations at these sites. Starting ~8,000 years ago in this area, sea level rose and the antecedent surface was initially flooded and eroded to remove sediment and soils. Reef accumulation began on the deeper (-16 m) shelf-edge reefs of Lang Bank and Buck Island Bar, then at Buck Island above the -15 m Pleistocene surface there. *A. palmata* on Buck Island Bar never caught up with sea level over its cored history (Fig. 15A).

The inner-shelf reef at Tague Bay initiated on a pre-transgression surface ranging from -12.5 to -15.5 m MSL. Although it appears from Figure 15D that reef-crest *A. palmata* re-established a facies on Tague Bay reef above -6 m MSL after a prolonged hiatus, we recognize that the reef crest facies critical to such an interpretation was only minimally cored and not dated, leaving significant periods of the geologic history of Tague Reef undocumented. At ~5000 years ago, as sea level continued to rise, the higher pre-Holocene surfaces westward to Long Reef were flooded, and a later episode of shallow water reef building occurred at Long Reef that appears to have kept pace with SLR to the present.

Outer Shelf-Edge Reef Complex

The progression of reef initiation along the outer shelf-edge reef trend follows the depth (decreasing to the west from Lang Bank towards Long Reef) of the Pleistocene surface (Hubbard et al., 2005), in context of Caribbean SLR in the region (Toscano and Macintyre 2003; Fig. 15A-D) intersecting the exposed shelf areas beginning about 8,000 years ago. Adey et al. (1977) studied the relict outer shelf-edge reef complex around the southeastern end of St Croix and noted that these reefs, although dominated by *A. palmata*, did not keep pace with early Holocene rates of SLR of 8 mm/yr (based on the sea-level curve of Neumann, 1971 and later revisions). They interpreted the demise of the shelf-edge reef system as coinciding with the flooding of the insular shelf and resulting turbidity from

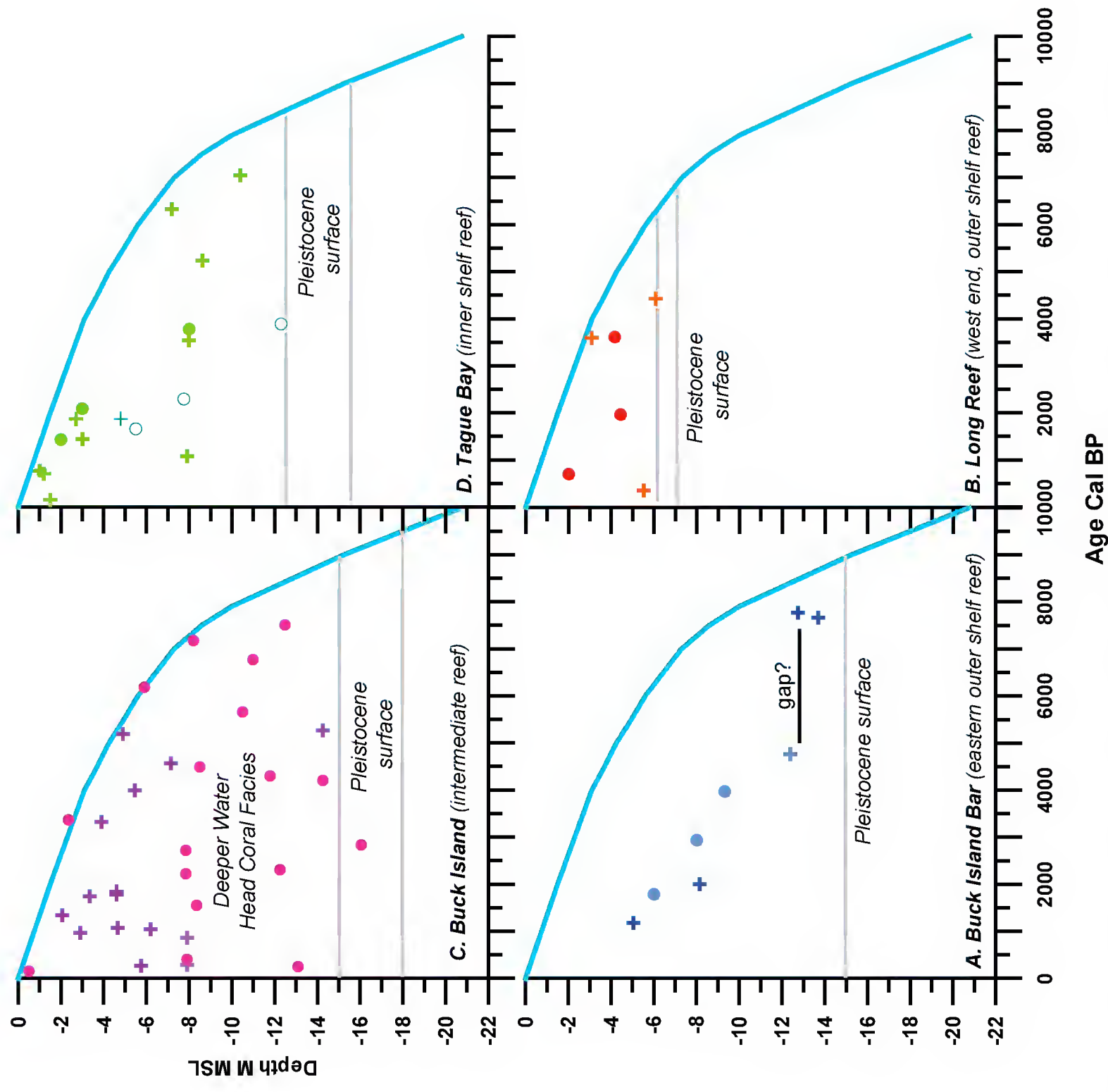


Figure 15. Radiocarbon- and TIMS- dated coral samples from the northeastern coast of St Croix plotted against the western Atlantic sea-level curve (Toscano and Macintyre 2003). This time-depth plot documents the progressive east-west shallowing of the antecedent surface and the various stages of development of each site. Buck Island Bar samples never attain depths of less than 4-5 m below sea level. There are currently no published age data for Lang Bank.

the erosion of shelf soils. Non-carbonate mineralogic evidence supporting this hypothesis from X-ray diffraction of reef sediments in cement crusts indicated the occurrence of clay minerals and other siliclastic components coinciding with the disappearance of *A. palmata* as a reef-framework builder (Adey et al., 1977).

In contrast to the southeastern shelf-edge reefs, two emergent northeastern shelf-edge complex reef communities at Buck Island Bar and its western end at Long Reef appeared to have kept pace with SLR. Adey et al. (1977) therefore interpreted these sites as being located in areas isolated from the insular shelf or adjacent to very narrow shelf areas and hence not significantly affected by shelf erosion turbidity “at 7000-8000 years BP.” These sites were thus expected to have maintained “continuous Holocene section[s] when cored” (p. 20).

A sequential history of the northern outer shelf-edge reef system begins ~8000 years ago when the *A. palmata* community presumably flourished on the northern flank of Lang Bank (Fig. 1), while the adjacent inner shelf was initially flooded by rising sea level (Hubbard, 1991). The thickness of the Holocene reef cover on the northern flank of Lang Bank is as yet unreported but may be similar to the 10.4 m reef section dominated by *A. palmata* and sand intervals (Core BB-1; Hubbard, 1991; Hubbard et al., 2005; Fig. 16) on Buck Island Bar, its western extension (Fig. 1). Buck Island Bar initiated by ~7,700 cal BP (Hubbard et al., 2005) above the -15 m to -16 m MSL deep Pleistocene surface as a shallow *A. palmata* reef (two samples from Hubbard et al., 2005; Fig. 15A), followed by a ~2,500 year coral gap (Fig. 15A; an artifact of limited coring?). This gap (also noted by Hubbard et al., 2005) appears to be real as the reef shows no significant framework accumulation of *A. palmata* at this site. If so, this gap may indeed have been caused by local shelf flooding and turbidity, or from another environmental cause. At about 4,000 years ago the reef record resumed (until ~1,200 cal BP) in a deeper water setting (Fig. 15A). Macintyre and Adey (1990) had previously drilled Core BB-2 slightly leeward of BB-1 (Fig. 16), from which they demonstrated that while this reef community tracked rising sea levels for the last 4,000 years (Fig. 15A), it consistently remained below sea level by ~5 meters (the depth of the drill site). Macintyre and Adey (1990) particularly noted the number of heavily cemented pavement limestone intervals and massive corals recovered in BB-2 (Fig. 16). The heavily cemented “pavement limestone” sections indicated long periods of exposure of the sea floor to allow lithification to take place (Macintyre, 1977; Macintyre and Marshall, 1988). In addition, they noted the deeper “anastomosing thickets of *A. palmata* on Buck Island Bar as considerably more fragile than their robust shallow-water counterparts” (p. 6). Thus they interpreted the paleoenvironment at core BB-2 as one of frequent heavy seas breaking and transporting fragile *A. palmata* from the site, leaving only the massive coral heads that grew on the pavement around the *A. palmata*. Hubbard (1991) downplayed the magnitude and destructive influence of waves and storms on *A. palmata* around St. Croix, and suggested that the coral heads and cemented pavement sections in core BB-2 were typical of a more protected back reef environment in comparison to the more exposed windward *A. palmata* dominated core site BB-1 (Fig. 16). However, Hubbard’s core BB-1 consisted predominantly of sand intervals, suggesting a lower energy fore-reef setting where sand could accumulate.

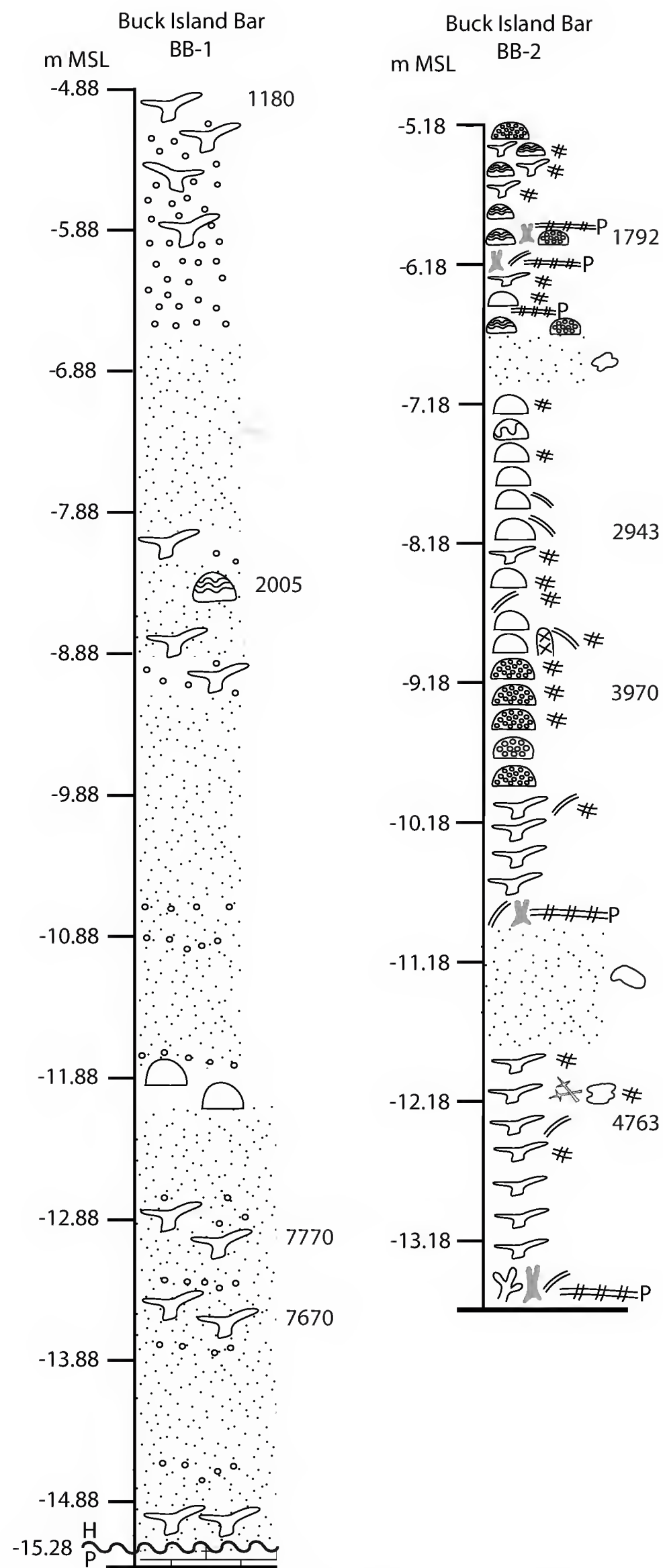


Figure 16. Core data from two cores drilled into Buck Island Bar (BB1-- Hubbard 1991; Hubbard et al., 2005) and (BB2 – Macintyre and Adey, 1990) showing the location of radiocarbon dates (after Hubbard, 1991; Hubbard et al., 2005).

The question remained, however, as to why Buck Island Bar's *A. palmata* reef community lagged behind SLR, as indicated by the youngest radiocarbon date of 1180 cal BP at the top of Hubbard's core BB-1 (-5 m MSL; Fig. 16). Figure 15A combines all coral dates from Buck Island Bar (Hubbard et al., 2005; Macintyre and Adey, 1990). Hubbard (1991) suggested that Buck Island Bar initiated before the oldest *A. palmata* date of 7770 cal BP (date from Hubbard et al., 2005) "during a period of very rapid sea-level rise" (Hubbard et al., 1991; p. 26) that presumably outpaced the accumulation rate of *A. palmata*. Although the deepest *A. palmata* samples at the base of core BB1 were not dated, the two oldest dates of 7770 and 7670 cal BP, at present depths of -12.75 and -13.7 m MSL respectively, appear to have grown in shallow water of no more than 3 m (Fig. 15A) and date to the oldest segment of the WASL curve when SLR was 5.2 mm/yr (Toscano and Macintyre, 2003; Fig. 15A), a rate slower than the growth rate capacity of *A. palmata*. These dates are followed, after the ~2,500 year gap, by a sample of *A. palmata* that grew in ~8 m water depths (close to their maximum) at 4763 cal BP, at which time the rate of SLR had decreased markedly to 1.47 mm/yr (Toscano and Macintyre, 2003; Fig. 15A). All subsequent *A. palmata* and head corals appear to have established as a deeper-water (10 to 5 m water depths) coral community on Buck Island Bar. It appears that whatever caused the 2,500 year gap in the coral record prevented reef accumulation while water depths simultaneously increased. When conditions again favored coral growth, water depth had increased sufficiently to cause attenuation of sunlight (required for coral/algal symbiosis) and thus reduce *A. palmata*'s ability to grow rapidly and catch up to sea level for the next 4000 years. We also speculate that in deeper water these *A. palmata* likely utilized a thin, upraised/outstretched branch growth habit to collect sufficient sunlight (as observed on site by Macintyre and Adey, 1990). Thinner coral branches would have been more susceptible to destruction by strong bottom currents generated by frequent heavy wave action on this exposed shelf edge. Such ongoing conditions are hypothesized to have contributed to limiting active reef accumulation at the shelf edge.

Interestingly, Hubbard (1991) reported that the northern reef communities on Lang Bank ceased active accumulation about 5,000 years ago. The Virgin Islands C&GS Chart 905 shows that the crest of the northern flank of Lang Bank has present water depths of about 9 to 11 meters. The WASL curve (Toscano and Macintyre, 2003; Fig. 15) indicates that 5,000 years ago sea level was at -4 m MSL, thus the *A. palmata* communities were growing in five to seven meter depths, or close to their maximum depth range, and not accreting reef framework as part of a reef crest keeping pace with SLR. Again, deeper water may have prevented "reef keep up" due to attenuation of light penetrating to these depths. In addition, the possibility remains that the upward growth of a fragile, deep water form of *A. palmata* was restricted or pruned by high energy conditions or frequent heavy seas.

On the western end of the outer shelf-edge reef system, Long Reef (Fig. 13) exhibits no more than 4.5 m accumulation of Holocene reef on top of a ~6-m higher, westward shallowing Pleistocene surface. The higher elevation of the Pleistocene surface at the western end of the outer shelf-edge reef (unknown to Macintyre and Adey, 1990), resulted in ~2500 yrs delay in the timing of reef initiation (at ~4,500 cal BP) until sea level rose above that surface. Framework began accumulating on the fore-reef spur at -6 m MSL (Fig 13). While no dates at the Pleistocene/Holocene unconformity are available for Core

2 just behind the reef crest (Fig. 13), stratigraphically higher ages in this core suggest that an estimate of >5,000 years ago would account for sufficiently high sea level (of ~2.5 m, Fig. 15B) over the -6 m MSL Pleistocene surface to support coral growth in a back-reef environment. Figure 15B illustrates the belated history of reef development in context of SLR at Long Reef. The few data are insufficient to determine how well the *A. palmata* facies kept pace with SLR over the 5,000 years of its existence; however the reef as a whole (including the head corals) appears to have tracked sea level consistently over that time.

Buck Island Reef, in its intermediate location between the outer shelf-edge reef at Buck Island Bar and the inner shelf reef at Tague Bay, appears to be contemporaneous with early reef initiation at Tague Reef as well as later reef development at Long Reef (Fig. 15C, D, B). The Pleistocene surface under Buck Island Reef is slightly deeper (-15 to -18 m) than that underlying Tague Reef (-12.5 to -15.5 m), hence the earlier initiation of reef growth at this more seaward location. With the exception of one deep (-14 m) *A. palmata* date (Fig. 15C), head corals dominate the reef facies at Buck Island Reef until ~5,000 cal BP. The depth of this *A. palmata* sample is inconsistent with the much shallower depths of two other *A. palmata* of similar age. Hubbard et al.'s (2005) corelog indicates an *A. palmata* and rubble interval at this depth below a head-coral facies. All cores from Buck Island Reef exhibit sand, rubble, voids and head corals in the lower few meters (Hubbard et al., 1991; 2005). This sample may indicate a deeper water form of *A. palmata* in the midst of a head coral facies contemporaneous with shallower reef crest *A. palmata* at this site. It is also possible that this sample was detrital, or represents a drilling cave-in fragment based on its age in comparison to more elevated samples.

Inner Bank-Barrier Reef Complex

The core transect across the bank-barrier reef off Tague Bay (Fig. 14) shows the optimum development of this reef system with 10 m of Holocene reef framework. This thickness, according to Burke et al. (1989), is related to the eastward dipping, deeper level of the Pleistocene limestone substrate (-12 m MSL compared to -6 m MSL underneath Long Reef), providing more space for thicker and earlier development of the reef. Sea level would have attained this surface at ~8,500 years BP, or at least 3,500 years earlier than at Long Reef. Burke et al. (1989) also postulated that the deeper antecedent surface would have allowed for earlier improvement of water conditions at this site following the flooding of the insular shelf and subsequent erosion of the sediment cover.

Figure 15D documents the history of Tague Reef in relation to SLR and the -12 to -13 m depth range of the Pleistocene surface under the reef. Although Tague Reef is part of the inner shelf reef trend, the depth of the Pleistocene surface there is similar to that underlying Buck Island Bar (-15 to -16 m). These reefs are therefore roughly contemporaneous despite their separate, parallel reef trends and histories. They differ in that Buck Island Bar (Fig. 15A) initiated almost 1000 years earlier, may have experienced a hiatus in *A. palmata* framework accumulation of ~2,500 years (based on only two available cores), then reestablished in a deeper environment wherein the reef could not catch up or keep up with SLR. The more protected inner shelf-reef trend in Tague Bay was able to track and even attain sea-level elevations over most of its time frame of existence, although according to Hubbard et al. (2005) Tague Reef and most of the inner shelf were

head coral-dominated before *A. palmata* framework took hold. Burke et al. (1989) suggested that staggered dates of reef initiation along the length of the reef reflected Tague Reef's beginning as a series of isolated patch reefs. Figure 15D (from our reef-normal cross section) suggests a hiatus in accumulation of *A. palmata* framework on Tague Reef from ~6,500 years ago to its apparent reestablishment just after ~2,000 years ago. This apparent hiatus occurred over a time of slow SLR of 1.47 mm/yr (Toscano and Macintyre, 2003), well below the regional accumulation rate of *A. palmata* framework of 2.6 mm/yr (James and Macintyre, 1985). The ultimate reality of this apparent hiatus cannot be ascertained owing to the lack of a dated reef-crest core, which might provide the paleoenvironmentally-specific samples needed to fill this gap. In addition, only the youngest and most elevated *A. palmata* from Tague Reef from Core 16 of Burke et al. (1989) has been radiocarbon dated.

CONCLUSIONS

Two coral-reef core transects provide further insight into the Holocene history of two parallel reef complexes of northeastern St. Croix. These new data further enhance previous coring, radiometric dating and geologic interpretations for the area. Reefs along the northeastern coast of St. Croix initiated sequentially from east to west along a westward-shallowing pre-Holocene surface as rising sea level breached, eroded and flooded these shelf areas in turn.

The eastern portions of the outer shelf-edge reef system have been previously studied (Lang Bank and Buck Island Bar). Our new transect across the Long Reef shelf-edge reef system (Fig. 13) represents the westernmost portion of the outer shelf-edge reef system extending from Buck Island Bar and Lang Bank. The westward-shallowing pre-transgression surface reaches a high point of -6 m MSL at Long Reef, resulting in a thinner (< 4.5 m) and younger Holocene cover compared to the thick (~10 m) Holocene section at Buck Island Bar. However, even the thicker eastern sections do not present long continuous records of Holocene reef accumulation to present sea level. The Lang Bank reefs stopped actively accumulating ~5,000 years ago according to Hubbard et al. (2005) in water depths of 5 to 7 meters. Buck Island Bar, where cored *A. palmata* remained at depths of -4.5 meters over the past 8,000 years and never caught up with sea level, stopped forming reef framework about 1,200 years ago when water depth was ~5 m. One core into Buck Island Bar offers evidence, in the form of leeward crest hard pavements, of potentially destructive high-energy conditions. It appears that the deeper depths for *A. palmata* growth resulted in this coral forming thinner, flatter, more fragile branches which could have been easily broken and transported during periods of severe wave action, resulting in a lack of reef accumulation.

The transect across the inner bank-barrier reef system off Tague Bay, by contrast, illustrates the optimum development of this reef with an accumulation of 10 m of Holocene deposits. The successful formation of this reef at this site appears to be the combination of accommodation space due to the depth of substrate and the possibility

that water conditions in this area improved rapidly following the flooding of the shelf and erosion of the sediment cover (Burke et al., 1989).

Implications of this study for reconstruction of reef history and sea level using core data indicate that single reef localities (or cores) are unlikely to provide a comprehensive record of local shelf evolution or sea-level rise. The spatial and temporal variations of a reef complex (e.g., the *outer shelf-edge reef complex*) indicate the variety of site-specific physical and environmental factors controlling reef location and affecting reef growth. In addition, the biases inherent in interpreting minimal core data (such as at Buck Island Bar) may result in incomplete or inaccurate reef history reconstructions, and insufficient data to identify, constrain and understand true gaps in the record of *A. palmata*. The regional Caribbean sea-level synthesis provides the needed context for understanding varying depths, age ranges and histories of the reef settings along the northeastern coast of St. Croix, given a sufficient number of core transect localities along the reef system. More data from northeastern St Croix, particularly from Buck Island Bar and eastern Lang Bank, will help to complete the history presented here.

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